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# THE SPECTROSCOPIC ORBIT OF THE PLANETARY COMPANION TRANSITING HD 209458[1]

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## ABSTRACT

We report a spectroscopic orbit with period $P = 3.52433 \pm 0.00027$ days for the planetary companion that transits the solar-type star HD 209458. For the metallicity, mass, and radius of the star, we derive [Fe/H] = $0.00 \pm 0.02$, $M_* = 1.1 \pm 0.1\ M_\odot$, and $R_* = 1.2 \pm 0.1\ R_\odot$. This is based on a new analysis of the iron lines in our HIRES template spectrum and also on the absolute magnitude, effective temperature, and color of the star, and it uses isochrones from four different sets of stellar evolution models. Using these values for the stellar parameters, we reanalyze the transit data and derive an orbital inclination of $i = 86.^\circ1 \pm 1.^\circ6$. For the planet, we derive a mass of $M_p = 0.69 \pm 0.05\ M_{\rm Jup}$, a radius of $R_p = 1.40 \pm 0.17\ R_{\rm Jup}$, and a density of $\rho = 0.31 \pm 0.07$ g cm$^{-3}$.

*Subject headings:* binaries: eclipsing — planetary systems — stars: individual (HD 209458) — techniques: radial velocities

## 1. INTRODUCTION

We report in this Letter on our spectroscopic observations of HD 209458, observations that led to the discovery of a transiting planet with an orbital period of 3.5 days.

We have been observing HD 209458 since 1997 August as one of the targets in two large independent radial-velocity surveys, both searching for extrasolar planets around solar-type stars. One program uses the high-resolution HIRES spectrograph (Vogt et al. 1994) on the Keck I telescope, while the other uses ELODIE (Baranne et al. 1996) on the 1.93 m telescope at Observatoire de Haute Provence (France). In 1999 June, after observations from both efforts showed that the radial velocity of HD 209458 was variable, additional frequent observations were obtained with ELODIE as well as with CORALIE (Queloz et al. 2000) on the new 1.2 m Swiss telescope at La Silla.

In 1999 August, the identity of HD 209458 and its orbital elements were provided to D. C. and T. M. B. so that they could look for transits with the STARE photometric instrument.[11] Two transits were successfully observed in September 1999 (Charbonneau et al. 2000, hereafter C00). An independent discovery in 1999 November of the planetary orbit, as well as the detection of a transit ingress, are reported by Henry et al. (2000).

Transit observations together with an orbital solution allow us to determine directly the mass, radius, and density of the planet, provided we have good estimates for the mass, radius, and limb darkening of the star (e.g., C00). We describe in this Letter our efforts to derive better estimates for these parameters.

## 2. OBSERVATIONS

One of the two radial-velocity projects, the results of which we report here, is the G Dwarf Planet Search (Latham 2000). The sample for this project is composed of more than 1000 targets whose effective temperatures, luminosities, chemical compositions, and Galactic-population memberships have been determined using precise Strömgren photometry (E. H. Olsen 1993, private communication). In addition, the radial velocities of these stars were known to be constant at a precision of 300–600 m s$^{-1}$, based on more than 10 yr of observations with the CORAVEL radial-velocity monitors (Mayor 1985) and the CfA Digital Speedometers (Latham 1992).

The observations for this project were performed with HIRES and its iodine gas-absorption cell (Marcy & Butler 1992) on the Keck I telescope. The G Dwarf Planet Search observing strategy is designed to carry out an initial reconnaissance of the sample stars, with the immediate goal of identifying the stars whose radial velocity is modulated with an amplitude of about 50 m s$^{-1}$ or larger. To increase the number of target visits, we concede velocity precision and therefore have exposed no longer than needed to achieve a precision of 10 m s$^{-1}$. Radial velocities are derived from the spectra with TODCOR (Zucker & Mazeh 1994), a two-dimensional correlation algorithm.

The other program whose results are presented here is the ELODIE planet search survey (Mayor & Queloz 1995a). After

[1] Some of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The other data were obtained at Observatoire de Haute-Provence (France) and with the 1.2 m Euler Swiss telescope at La Silla Observatory, ESO Chile.

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[11] See T. M. Brown & D. Kolinski 1999, http://www.hao.ucar.edu/public/research/stare/stare.html.

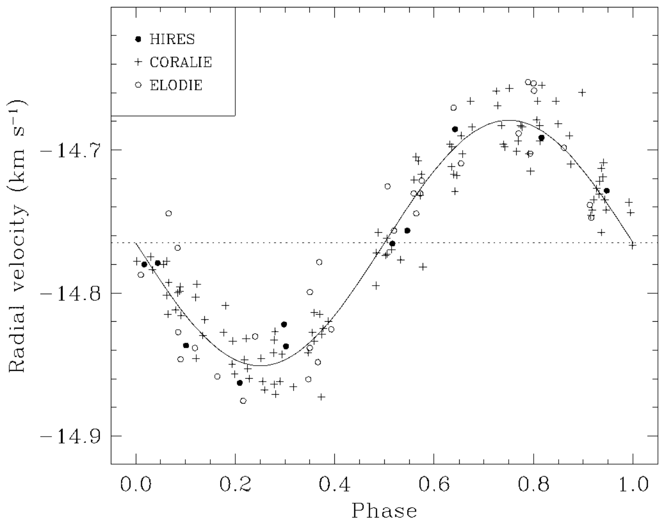


FIG. 1.—Radial velocities of HD 209458 plotted as a function of orbital phase for the solution detailed in Table 1. The measurements of the three observational programs are represented by different symbols.

the discovery of the planetary companion around 51 Peg (Mayor & Queloz 1995b), the surveyed sample was extended to about 320 northern hemisphere solar-type stars brighter than $m_V = 7.65$ and with small projected rotational velocities ($v \sin i$ from CORAVEL; Benz & Mayor 1984). From CORAVEL data, the stars in this sample were known to have constant radial velocities at a 300 m s$^{-1}$ precision level. Radial-velocity measurements are obtained with the ELODIE echelle fiber-fed spectrograph (Baranne et al. 1996) mounted on the Cassegrain focus of the 1.93 m telescope of the Observatoire de Haute-Provence. The reduction technique used for this sample is known as the "simultaneous thorium-argon technique" described by Baranne et al. (1996). The precision achieved with this instrument is of the order of 10 m s$^{-1}$ over more than 3 yr.

After the two independent detections of the short-term variability of HD 209458 by the HIRES and ELODIE teams, we decided to add this object to the CORALIE planet search sample (Udry et al. 2000a, 2000b) in order to gather more radial-velocity data and therefore increase the precision of the orbital elements. The precision achieved with CORALIE is of the order of 7–8 m s$^{-1}$ over 18 months. To check for other possible sources of line shifts besides orbital motion, we computed the mean bisector profiles (as described by D. Queloz et al. 2000, in preparation) for all the ELODIE and CORALIE spectra. No correlation between the observed velocities and the line profiles was detected, convincing us that the planetary interpretation was correct even before transits were detected.

## 3. RADIAL-VELOCITY ANALYSIS

As of 1999 November 16, we had a total of 150 radial-velocity measurements of HD 209458 available for analysis: 11 from HIRES, 31 from ELODIE, and 108 from CORALIE. Initially we applied shifts of $-5$ m s$^{-1}$ to the ELODIE velocities and $-14{,}780$ m s$^{-1}$ to the HIRES measurements to bring them to the CORALIE system, the latter offset being much larger due to the arbitrary zero point of the HIRES velocities (S. Zucker, G. A. Drukier, & T. Mazeh 2000, in preparation). To account for possible errors in these shifts, the orbital solutions described below included two additional free parameters—$\Delta_{\rm H-C}$ and $\Delta_{\rm E-C}$ for the HIRES and ELODIE shifts—along with the orbital elements.

TABLE 1
ORBITAL SOLUTION FOR HD 209458

| Parameter | Value |
|---|---|
| Period ....... | 3.52433 ± 0.00027 days |
| $\gamma$ ............ | $-14.7652 \pm 0.0016$ km s$^{-1}$ |
| K ........... | 85.9 ± 2.0 m s$^{-1}$ |
| $e$ ............ | 0 (fixed) |
| $T_c$ ........... | 2,451,430.8238 ± 0.0029 HJD |
| $M_p \sin i$ ...... | $0.685 \pm 0.018\ (M_* /1.1\ M_\odot)^{2/3}\ M_{\rm Jup}$ |
| $\Delta_{\rm H-C}$ ......... | $+0.2 \pm 4.7$ m s$^{-1}$ |
| $\Delta_{\rm E-C}$ ......... | $+0.5 \pm 5.1$ m s$^{-1}$ |
| $\sigma_{\rm H}$ ........... | 13.8 m s$^{-1}$ |
| $\sigma_{\rm E}$ ........... | 25.1 m s$^{-1}$ |
| $\sigma_{\rm C}$ ........... | 17.6 m s$^{-1}$ |

In addition, the two transit timings recorded by C00 provide useful information on the orbital period and $T_c$, the time of inferior conjunction. These timings were therefore included in the derivation of the spectroscopic orbital elements, and we treated them as independent measurements with their corresponding uncertainties.

In a preliminary solution, weights were assigned to each observation based on the internal errors. From this fit we computed the rms residuals separately for each data set—$\sigma_{\rm H}$, $\sigma_{\rm E}$, and $\sigma_{\rm C}$—and then scaled the internal errors for each instrument to match the corresponding rms residuals on average. We resolved for the orbital parameters, and the procedure converged in one iteration with essentially no change in the elements.

Tests allowing for a noncircular Keplerian orbit for HD 209458 resulted in an eccentricity indistinguishable from zero: $e = 0.016 \pm 0.018$. We therefore assume in the following that the orbit is circular. Our final orbital solution is represented graphically in Figure 1. The elements are given in Table 1, where the value of the planetary mass $M_p$ depends on the inclination angle and on the adopted stellar mass $M_*$ to the power of $\frac{2}{3}$. The orbital elements reported by Henry et al. (2000) are consistent with our results, although their quoted errors are substantially larger. Robichon & Arenou (2000) have identified three transits in the *Hipparcos* photometry and have derived a more precise period, $P = 3.524739 \pm 0.000014$ days, consistent with the value of Table 1 within 1.5 $\sigma$.

## 4. STELLAR PARAMETERS

In this section, we compare theoretical stellar-evolutionary models with observational parameters of HD 209458 in order to derive the stellar mass and radius, as done for other parent stars by Ford, Rasio, & Sills (1999). We use the stellar absolute visual magnitude together with either the effective temperature or the $B-V$ color. The comparison between the models and the observed $B-V$ is somewhat less secure, as the derivation of $B-V$ in the evolutionary models depends on the color-temperature calibration, for which the various models adopt slightly different prescriptions. The effective temperature, on the other hand, is well defined in the models and can be derived from the stellar spectra independently of the color. Both approaches compare the observed $M_V$ with the value derived in the models, a comparison which depends on the bolometric correction. However, the difference between the bolometric correction used by the various models is quite small.

The stellar models depend on the chemical abundance, and therefore a critical first step for both approaches is to determine the metallicity. An analysis of eight spectra obtained with the CfA Digital Speedometers (Latham 1992) with the techniques reported by Carney et al. (1987) gave $T_{\rm eff}$ = 5975 K, log $g$ = 4.25, and metallicity [$m$/H] = +0.11 ± 0.1. Another independent analysis of the cross-correlation dips from CORAVEL observations (Mayor 1980 as revised by Pont 1997 using primary calibrators by Edvardsson et al. 1993) gave [Fe/H] = −0.14 ± 0.1.

This large range in metallicity values, −0.14 to +0.11, implied a large uncertainty in the mass and radius of HD 209458, so we undertook a detailed analysis of selected Fe I and Fe II lines measured on our HIRES template spectrum, which has a resolving power of about 70,000 and signal-to-noise ratio per resolution element of about 300. We adopted a line list developed by L. de Almeida (1999, private communication) and solar *gf* values based on the National Solar Observatory solar flux atlas (Kurucz, Furenlid, & Brault 1984). We used model atmospheres and computer codes based on the work of R. L. Kurucz. Selected weak Fe I lines were used to adjust $T_{\rm eff}$ until the plot of abundance versus excitation potential was flat. This is the estimate of effective temperature that we used in the first of our comparisons with the stellar evolution models. Stronger Fe I lines were then included and the microturbulent velocity was adjusted to get a flat dependence of abundance on line strength. Finally, the surface gravity was adjusted until the abundances from the Fe II and Fe I lines agreed.

This analysis gave $T_{\rm eff}$ = 6000 K, microturbulent velocity $\xi$ = 1.15 km s$^{-1}$, log $g$ = 4.25, and [Fe/H] = 0.00. The errors in these values are undoubtedly dominated by systematic effects, and we estimate that they are ±50 K in $T_{\rm eff}$, ±0.2 in log $g$, and ±0.02 in [Fe/H].

In the other comparison, we use the observed color instead of the effective temperature. We adopt the $B-V$ value of +0.574 ± 0.014 (Perryman 1997) from the Tycho catalog, derived directly from the satellite measurements, and converted to the Johnson system, assuming no reddening. We prefer this value to the *Hipparcos*-listed ground-based value of $B-V$ = +0.594 ± 0.015, since we have been unable to trace the original source for the ground-based value in the published literature.

For the luminosity we rely on the accurate distance available from the *Hipparcos* astrometric mission (Perryman 1997), which when combined with the apparent magnitude yields an absolute visual magnitude. Several consistent measurements of $V$ are available, including Olsen (1983, 1994) and the one derived from the Tycho $V_T$ magnitude. The differences are minor, and for the purpose of this Letter we adopt the value derived from the *Hipparcos* measurement, 7.645 ± 0.002, which has the smallest uncertainty. The absolute visual magnitude we derive is $M_V$ = 4.28 ± 0.10, assuming no extinction.

In Table 2 we compare the values of the stellar mass $M_*$, radius $R_*$, and age derived for HD 209458, using $M_V$ together with either $T_{\rm eff}$ or $B-V$. This is done by considering isochrones from four different stellar evolution codes: Geneva (Schaller et al. 1992), Padova (Bertelli et al. 1994), Claret (Claret 1995), and Yale (Yi, Demarque, & Oemler 1997). The results of this comparison are given in Table 2.

Note that three sets of evolutionary models and the two comparisons yield similar results for the stellar mass and radius, with only small differences. The similar results are not surprising, since the Tycho value for $B-V$ corresponds to a temperature of 5935 K, according to the empirical calibration of Alonso, Arribas, & Martínez-Roger (1996), quite close to our own spectroscopic determination. Our $T_{\rm eff}$ determination is also consistent with observations in the Strömgren system, for which there are two independent measurements (Olsen 1983, 1994). The average of these two (following the recommendation of Olsen 1994) leads to a temperature of 5965 K, using again the calibration of Alonso et al. (1996). Only the Bertelli model gives a slightly larger mass, younger age, and smaller radius in the $M_V$ vs. $B-V$ comparison. This is probably because of a different color-temperature calibration. The larger spread and slightly older ages in the right-hand side of the table are also related to this effect.

TABLE 2

The Mass and Radius of HD 209458

| Code | Model $Z$ | Model $Y$ | $M_V$ vs. $T_{\rm eff}$ Age (Gyr) | $M_V$ vs. $T_{\rm eff}$ $M_*$ ($M_\odot$) | $M_V$ vs. $T_{\rm eff}$ $R_*$ ($R_\odot$) | $M_V$ vs. $B-V$ Age (Gyr) | $M_V$ vs. $B-V$ $M_*$ ($M_\odot$) | $M_V$ vs. $B-V$ $R_*$ ($R_\odot$) |
|---|---|---|---|---|---|---|---|---|
| Geneva | 0.02 | 0.30 | 4.3 | 1.10 | 1.19 | 5.3 | 1.09 | 1.23 |
| Bertelli | 0.02 | 0.27 | 4.5 | 1.08 | 1.19 | 1.9 | 1.13 | 1.14 |
| Claret | 0.02 | 0.28 | 4.5 | 1.11 | 1.19 | 6.5 | 1.08 | 1.25 |
| Yale | 0.02 | 0.27 | 4.9 | 1.10 | 1.20 | 5.6 | 1.09 | 1.22 |

We also investigated the effect of changing the helium abundance $Y$ and metal content $Z$. Since the stellar metallicity is near solar, the effect on the planetary mass and radius derived below is negligible.

Based on all these considerations, we adopt for our best estimate of the mass and radius of HD 209458 the values 1.1 ± 0.1 $M_\odot$ and 1.2 ± 0.1 $R_\odot$. The uncertainty estimates are somewhat arbitrary and are based mainly on the assumed uncertainty in $T_{\rm eff}$, $M_V$, and $B-V$. For comparison, Allende Prieto & Lambert (1999), who used the Bertelli et al. (1994) model, derived for HD 209458 $M_*$ = 1.03 ± 0.11 $M_\odot$, $T_{\rm eff}$ = 6030 ± 140 K, and a radius of $R_*$ = 1.15 ± 0.08 $R_\odot$. In an earlier version of this work, we used the spectroscopically derived surface gravity for the comparison with the models, which resulted in a stellar radius of 1.3 $R_\odot$. We favor the present analysis, as the temperature determination is more reliable (e.g., Ford et al. 1999).

Using ELODIE and CORAVEL cross-correlation dip widths, we infer the projected rotational velocity (calibration by Queloz et al. 1998 for ELODIE and by Benz & Mayor 1984 for CORAVEL). The results are $v \sin i$ = 4.4 ± 1 km s$^{-1}$ for CORAVEL and $v \sin i$ = 4.1 ± 0.6 km s$^{-1}$ for ELODIE.

## 5. PLANETARY PARAMETERS

C00 present preliminary estimates of the planetary radius $R_p$ and orbital inclination $i$ based on initial estimates of $M_*$, $R_*$, and the $R$-band limb-darkening parameter $c_R$. We now present values for these quantities based on the more accurate analysis of the stellar parameters adopted in this Letter. In addition, we give estimates of the uncertainties that combine the effects both due to the uncertainties in the stellar parameters and due to the level of precision in the photometric measurements of the transit. All uncertainties presented below correspond to 1 $\sigma$ confidence levels.

Using the calculated limb darkening coefficients presented in Claret, Díaz-Cordovés, & Giménez (1995), we adopted a value of $c_R$ = 0.56 ± 0.03 based on the values for $T_{\rm eff}$ and log $g$ derived in the previous section. As described in C00, we then calculated the $\Delta\chi^2$ of the photometric points for the model light curve as a function of $R_p$ and $i$, using the revised values of $\{M_*, R_*, c_R\}$ presented here. To evaluate the uncertainty in the derived values of $R_p$ and $i$, we calculated the $\Delta\chi^2$ for all combinations of the stellar parameters at 1 $\sigma$ above and below their respective best-fit values. We then assign 1 $\sigma$ error bars based on the intervals which are excluded with this confidence for all these combinations.

We find $R_p = 1.40 \pm 0.17\ R_{\rm Jup}$ and $i = 86^\circ\!.1 \pm 1^\circ\!.6$. The primary mass and the inclination imply (see Table 1) that the planetary mass is

$$M_p = 0.69 \pm 0.05\ M_{\rm Jup}.$$

From the planetary radius and mass we calculate the density, surface gravity, and escape velocity to be $\rho = 0.31 \pm 0.07$ g cm$^{-3}$, $g = 870 \pm 160$ cm s$^{-2}$, and $v_e = 42 \pm 4$ km s$^{-1}$.

In the interpretation of the transit curve of HD 209458, the dominant uncertainty in the planetary parameters is due to the uncertainty in the stellar radius, rather than the observational uncertainty in the photometric points.

The planetary radius found here is slightly larger and the orbital inclination is smaller than the values presented in C00. This is due primarily to the fact that the value of the stellar radius found here (1.2 $R_\odot$) is slightly larger than the one assumed in the initial analysis (1.1 $R_\odot$). A larger star requires a larger planet crossing at a lower inclination to fit the same photometric data. The results presented here and in C00 are based on the analysis of the detailed observed transit light curve. Henry et al. (2000), who did not observe the full transit, assumed a value of 90° for the orbital inclination, and a stellar radius and mass of 1.15 $R_\odot$ and 1.03 $M_\odot$. With these assumptions they derived a planetary mass and radius of $R_p = 1.42 \pm 0.08 R_{\rm Jup}$ and $M_p = 0.62 M_{\rm Jup}$.

## 6. DISCUSSION

The spectroscopic orbit, when combined with the inclination derived from transits, enables us to derive the planetary mass directly. This demonstrates the power of combining spectroscopy and photometry for transiting planets (C00; Henry et al. 2000). To derive masses for nontransiting planets that have spectroscopic orbits, we are forced to turn to other approaches for determining the orbital inclination, such as astrometry (e.g., Mazeh et al. 1999; Zucker & Mazeh 2000).

In principle we might be able to derive the inclination of the stellar rotational axis, if we could obtain the stellar rotational period from photometric observations. Together with the projected rotational velocity and the stellar radius derived here, this will enable us for the first time to check the assumption that the stellar rotation is aligned with the orbital motion for such short-period systems. With $v \sin i = 4.2 \pm 0.5$ km s$^{-1}$, alignment implies a rotational period of $P = 14.4 \pm 2.1$ days.

One unique feature of the transit technique is its ability to derive the planetary radius. As described in the review by Guillot (1999) and the references listed therein, the radius of an extrasolar giant planet is determined by its mass, age, degree of insolation, and composition. Now that an accurate measurement of the planetary radius has been made, it should be possible to infer specifics of the planetary composition, since the mass and insolation are known, and the age can be reasonably constrained based on the value of the age of the star determined above. More specifically, as described in Guillot (1999), it may be possible to calculate the amount of heavy elements for a given hydrogen/helium ratio and to infer the presence or absence of certain atmospheric grains.

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